The Need for an early $\bar{\nu}$ run of NOνA

S. Uma Sankar

Department of Physics
Indian Institute of Technology Bombay
Mumbai, India

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Neutrino Highlights before 80s

- Existence of Neutrinos predicted by Pauli to rescue energy-momentum conservation in beta decay, followed by Fermi theory.
- Cowan-Reines experiment established the existence of the first (electron) (anti-)neutrino.
- Goldhaber experiment measured the helicity of the neutrino to be left-handed.
- Brookhaven second neutrino experiment established the existence of the second (muon) neutrino.
- Davis Solar neutrino experiment: Detected the electron neutrinos from the sun but found only one third of the expected flux.
- Gargamelle experiment, at CERN, established the weak neutral currents.

Neutrino Revolution in 80s

- Mikheyev-Smirnov proposed a very imaginative solution to the solar neutrino deficit based on neutrino oscillations.
- Observation of neutrinos emitted by SN1987A by IMB and KamiokaNDE.
- The same two experiments detected the muon neutrinos produced in the atmosphere. They found that the flux of upward going neutrinos is about 60% of the flux of downward going neutrinos.

Nucleon Decay Experiment morphed into Neutrino Detection Experiment.

Three flavor neutrino oscillations became serious candidates to explain both solar and atmospheric neutrino deficits.

The need to verify this hypothesis led to a plethora of neutrino oscillation experiments with both natural and man-made sources.

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Three flavor Neutrino Oscillations

- The three neutrino flavors, ν_e, ν_μ and ν_τ, mix to form three mass eigenstates ν_1, ν_2 and ν_3.
- $|\nu_\alpha\rangle = U|\nu_i\rangle$ where U is a 3×3 unitary matrix ($\alpha = e, \mu, \tau$ and $i = 1, 2, 3$).
- U is parametrized in terms of 3 mixing angles (similar to Euler angles) and one phase (similar to the quark case, as done by Kobayashi and Maskawa).
- Oscillation probabilities depend on the above four quantities and the two independent mass-squared differences $\Delta_{21} = m_2^2 - m_1^2$ and $\Delta_{31} = m_3^2 - m_1^2$.
- The mass-squared differences, needed to explain the solar and atmospheric neutrino deficits, are widely different. So it is assumed that Δ_{21} drives the solar neutrino oscillations and Δ_{31} the atmospheric neutrino oscillations.

- Mass-squared difference scale for solar neutrinos $\sim 10^{-5}$ eV^2 and that for atmospheric neutrinos $\sim 10^{-3}$ eV^2.
- CHOOZ experiment detected the neutrinos from a reactor at a distance of 1 km.
- The measured ratio of observed/expected number of events is $R = 1.01 \pm 2.8\% \pm 2.7\%$
  CHOOZ Collaboration: hep-ex/9711002 and hep-ex/9907037
- The first paper to analyze the CHOOZ result in three flavor oscillation framework and derive the upper limit $\sin^2 2\theta_{13} \leq 0.1$.
  Mohan Narayan, G. Rajasekaran and S. Uma Sankar, hep-ph/9712409.
- Also combined this with solar neutrino data and derived the upper limit $\theta_{13} \leq 9^\circ$.
- There are two small quantities $\alpha = \Delta_{21}/\Delta_{31}$ and θ_{13} among the neutrino oscillation parameters.

- In the present convention, the mass eigenstates are labelled based on their ν_e content. ν_1 has the largest (about 60%), ν_2 has intermediate (about 30%) and ν_3 has the smallest (a little less than 10%).
- Setting $\theta_{13} = 0$ in solar neutrino oscillations and KamLAND experiment, leads to a two flavor $\nu_e/\bar{\nu}_e$ survival probability in terms of Δ_{21} and θ_{12}.
- Setting both $\alpha = 0$ and $\theta_{13} = 0$ in atmospheric neutrino oscillations and MINOS experiment, also gives a two flavor $\nu_\mu/\bar{\nu}_\mu$ survival probability, which is defined by Δ_{31} and θ_{23}.
- Setting $\alpha = 0$ in short baseline $(L \sim 1\ km)$ reactor neutrino experiments leads to a two flavour survival probability in terms of Δ_{31} and θ_{13}
- The measured energy dependence of solar neutrino survival probability requires Δ_{21} to be positive. So far no data on sign of Δ_{31}.
- For Δ_{31} positive, we have the pattern $m_3 \gg m_2 > m_1$ called normal hierarchy (NH). For Δ_{31} negative, the pattern is $m_2 > m_1 \gg m_3$, called inverted hierarchy (IH).

Present values of Oscillation parameters

Analysis of all the oscillation experiments together gives us the following values for neutrino oscillation parameters.

- $\sin^2\theta_{12} = 0.30 \pm 0.013$ (solar mixing angle)
- $\sin^2\theta_{23} = 0.41^{+0.037}_{-0.025}$ OR $0.59^{+0.021}_{-0.022}$ (atmospheric mixing angle)
  Degenerate solutions for θ_{23} in lower octant (LO) and higher octant (HO) coming from the MINOS measurement showing non-maximal $\sin^2 2\theta_{23}$.
  MINOS Collaboration: R. Nichol, Talk at *Neutrino 2012*, Kyoto, and P. Adamson *et al*, arXiv:1304:6335.
- $\Delta_{21} = (7.50 \pm 0.185) \times 10^{-5} eV^2$ (solar mass-squared difference)
- $|\Delta_{31}| = (2.47^{+0.069}_{-0.067}) \times 10^{-3} eV^2$ (atmospheric mass-squared difference)
- $\sin^2\theta_{13} = 0.023 \pm 0.0023$. (Big excitement of 2012 in Neutrino Physics)

[Gonzalez-Garcia, Maltoni, Salvado, Schwetz, arXiv:1209.3023]

Current Long Baseline Experiments

- Measurements still to be made:
  - Neutrino mass hierarchy (Is $m_3 >> m_2 > m_1$ or $m_2 > m_1 >> m_3$?)
  - Octant of θ_{23} ($\theta_{23} < \pi/4$ (LO) or $\theta_{23} > \pi/4$ (HO)?)
  - Evidence for CP violation $(\delta_{CP} \neq 0, 180^\circ)$
  - Measurement of δ_{CP}.
- $\nu_\mu \to \nu_e$ oscillation probability at long baseline experiments depends on the small parameters, θ_{13} and α, and is a genuine three flavor quantity.
- It also depends on all the above unknowns and is being measured by T2K and NOνA.
- The resultant parameter degeneracies limit the ability of the experiments to make effective measurements.

$|\nu_\mu\rangle \longrightarrow |\nu_e\rangle$ Oscillation with Matter Effect in Long Baseline Experiments

$$
\begin{aligned}
P_{\mu e} \quad &= \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 \hat{\Delta}(1-\hat{A})}{(1-\hat{A})^2} \\
+ \quad & \alpha \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\hat{\Delta} + \delta_{CP}) \\
& \frac{\sin \hat{\Delta}\hat{A}}{\hat{A}} \frac{\sin \hat{\Delta}(1-\hat{A})}{1-\hat{A}} \\
+ \quad & \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{13} \cos^2 \theta_{23} \frac{\sin^2 \hat{\Delta}\hat{A}}{\hat{A}^2}
\end{aligned}
$$

[Cervera et al., hep-ph/0002108, M. Freund, hep-ph/0103300]

$\hat{\Delta} = \Delta_{31} L/4E$, $\hat{A} = A/\Delta_{31}$, $\alpha = \Delta_{21}/\Delta_{31}$

$|\nu_\mu\rangle \longrightarrow |\nu_e\rangle$ Oscillation with Matter Effect in Long Baseline Experiments

- $\sin 2\theta_{13} \approx 0.3$ and $\alpha \approx 0.03$. So α^2 term can be ignored.
- Δ_{31} +ve for NH and -ve for IH
- A +ve for ν and -ve for $\bar{\nu}$
- For ν, $\hat{A}$ +ve for NH and -ve for IH
- For $\bar{\nu}$, $\hat{A}$ -ve for NH and +ve for IH
- $P_{\mu e}$ SENSITIVE to hierarchy
- $P_{\mu e}$ dependent of θ_{13}, hierarchy, octant of θ_{23}, δ_{CP}

Degeneracies in hierarchy determination

- In this talk, I will concentrate on the determination of hierarchyr, which is within the reach of the current and upcoming experiments.
- But this determination is subject to the following degeneracies:
  - The (hierarchy-δ_{CP}) degeneracy:$P_{\mu e}(\theta_{13}, \mathrm{NH}, \delta_{CP}) = P_{\mu e}(\theta_{13}, \mathrm{IH}, {\delta_{CP}}')$
  - The (hierarchy-θ_{13}) degeneracy: $P_{\mu e}(\mathrm{NH}, \theta_{13}, \delta_{CP}) = P_{\mu e}(\mathrm{IH}, {\theta_{13}}', \delta_{CP})$
  - The (hierarchy-octant) degeneracy: $P_{\mu e}(\mathrm{NH}, \theta_{23}, \theta_{13}, \delta_{CP}) = P_{\mu e}(\mathrm{IH}, 90^\circ - \theta_{23}, \theta_{13}, {\delta_{CP}}')$

  [Barger et al., arXiv: hep-ph/0112119]
- Because of the first degeneracy, it is important to determine hierarchy before attemtpting to measure δ_{CP}.

The Hierarchy-δ_{CP} Degeneracy

[Barger et al., arXiv: hep-ph/0112119; Mena, Parke, arXiv: hep-ph/040870]

$$
\begin{aligned}
P_{\mu e} &= \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 \hat{\Delta}(1-\hat{A})}{(1-\hat{A})^2} \\
+ & \alpha \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\hat{\Delta} + \delta_{CP}) \\
& \frac{\sin \hat{\Delta}\hat{A}}{\hat{A}} \frac{\sin \hat{\Delta}(1-\hat{A})}{1-\hat{A}}
\end{aligned}
$$

- $P_{\mu e}$ (NH) $>$ $P_{\mu e}$ (IH), for ν: consequence of $\hat{A}$ dependence
- At oscillation maxima $\hat{\Delta} \simeq 90^\circ$
- $\cos(\hat{\Delta} + \delta_{CP})$ is 1 for $\delta_{CP} = -90^\circ$ and -1 for $\delta_{CP} = 90^\circ$
- For $\bar{\nu}$, $\hat{A}$ and δ_{CP} change sign. This leads $P_{\mu e}$ (NH) $<$ $P_{\mu e}$ (IH), for $\bar{\nu}$:

The Hierarchy-δ_{CP} Degeneracy in NOνA

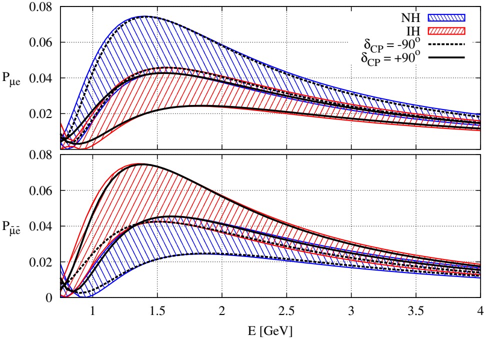

Figure: $P_{\mu e}$ (top panel) and $P_{\bar{\mu}\bar{e}}$ (bottom panel) vs. energy for NOνA. Variation of δ_{CP} leads to the blue (red) bands for NH (IH). The plots are drawn for maximal θ_{23} and other neutrino parameters given as the central values in slide 7.

[Suprabh Prakash, Sushant Raut, S. Uma Sankar, arXiv: 1201.6485v3]

Favorable and Unfavorable Combinations

- $P_{\mu e}(NH, -180^\circ < \delta_{CP} < 0) > P_{\mu e}(IH, \text{any } \delta_{CP})$
- $P_{\bar{\mu}\bar{e}}(NH, -180^\circ < \delta_{CP} < 0) < P_{\bar{\mu}\bar{e}}(IH, \text{any } \delta_{CP})$
- $P_{\mu e}(IH, 0 < \delta_{CP} < 180^\circ) < P_{\mu e}(NH, \text{any } \delta_{CP})$
- $P_{\bar{\mu}\bar{e}}(IH, 0 < \delta_{CP} < 180^\circ) > P_{\mu e}(NH, \text{any } \delta_{CP})$
- For these two cases NOνA can determine hierarchy if statistics are large enough.
- $P_{\mu e}(NH, 0 < \delta_{CP} < 180^\circ) \simeq P_{\mu e}(IH, -180^\circ < \delta_{CP}{}' < 0)$
  $P_{\bar{\mu}\bar{e}}(NH, 0 < \delta_{CP} < 180^\circ) \simeq P_{\bar{\mu}\bar{e}}(IH, -180^\circ < \delta_{CP}{}' < 0) \longrightarrow$
  DEGENERATE solutions- (true hierarchy, δ_{CP}) and (wrong hierarchy, $\delta_{CP}{}'$) for each measurement, no hierarchy determination
- (NH, δ_{CP} in LHP) and (IH, δ_{CP} in UHP) are favorable combinations for hierarchy determination in NOνA.
- (NH, δ_{CP} in UHP) and (IH, δ_{CP} in LHP) are unfavorable combinations for hierarchy determination in NOνA.

[Suprabh Prakash, Sushant Raut, S. Uma Sankar, arXiv: 1201.6485v3]

Potential for NOνA

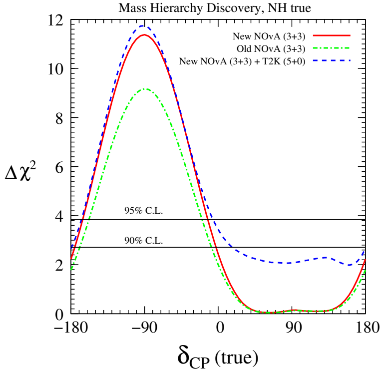

Figure: Hierarchy sensitivity for NOνA after complete run. In the left (right) panel, the true hierarchy is taken to be NH (IH).

[Sanjib Agarwalla, Suprabh Prakash, Sushant Raut, S. Uma Sankar, arXiv: 1208.3644v2]

An Aside: Hierarchy-δ_{CP} degeneracy for LBNE

- This degeneracy will limit the capability of LBNE also, especially if θ_{23} is in LO.
- For θ_{23} in LO and for the most unfavorable value of δ_{CP}, LBNE will not be able to get a 3σ hierarchy determination.
- But, addition of T2K and NOνA data, will improve the hierarchy determination of LBNE to better than 3σ level, even for the most unfavorable parameter values.

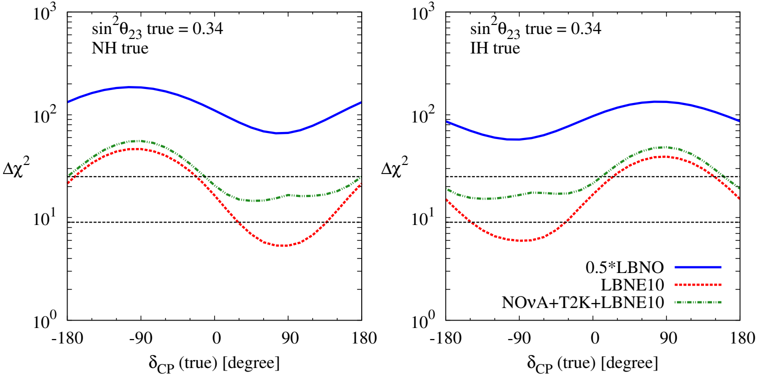

Figure: Hierarchy sensitivity for LBNE+NOνA+T2K. In the left (right) panel, the true hierarchy is taken to be NH (IH).

[Sanjib Agarwalla, Suprabh Prakash, S. Uma Sankar, arXiv: 1304.3251v2]
[Elizabeth Worcester, Talk at *EPS-HEP conference 2013*, Stockholm.]

Aim of the Work

We limit ourselves to favorable hierarchy-δ_{CP} combinations so that we do not have to worry about the most serious degeneracy.
We ask, "What can we learn from the first 3 years data of NOνA?"
We consider two possibilities.

- 3 year of ν run
- 1.5 year ν run + 1.5 year $\bar{\nu}$ run

WHY?

- Originally first 3 year ν run was considered to discover non-zero θ_{13}, in case it was small.
- But now θ_{13} is established to be non-zero at high confidence level and is measured to be moderately large ($\simeq 8^\circ$).
- So must consider which run combination has best chance to give an early hint of hierarchy.

[Suprabh Prakash, Ushak Rahaman, S. Uma Sankar, arXiv:1306.4125]

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Residual degeneracies in NOνA ν data

Pure neutrino data it is subject to some residual degeneracies.

$$
\begin{aligned}
P_{\mu e} &= \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 \hat{\Delta}(1-\hat{A})}{(1-\hat{A})^2} \\
+ & \quad \alpha \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\hat{\Delta}+\delta_{CP}) \\
& \quad \frac{\sin \hat{\Delta}\hat{A}}{\hat{A}} \frac{\sin \hat{\Delta}(1-\hat{A})}{1-\hat{A}}
\end{aligned}
$$

- Because we decided to limit ourselves to favorable half-planes of δ_{CP}, the second term does not affect degeneracies too much.
- If the precision in θ_{13} is not very good, then hierarchy-θ_{13} degeneracy limits the hierarchy determination ability.

Residual degeneracies in NOνA ν data

- For example, let us assume NH is the true hierarchy. The combination $P_{\mu e}(\text{NH}, \theta_{13})$ can be faked by $P_{\mu e}(\text{IH}, {\theta_{13}}' > \theta_{13})$.
- But $P_{\bar{\mu}\bar{e}}(\text{NH}, \theta_{13})$ will be much lower than $P_{\bar{\mu}\bar{e}}(\text{IH}, {\theta_{13}}' > \theta_{13}))$.
- In other words, the fake hierarchy solutions, due to hierarchy-θ_{13} degeneracy, occur at different values of ${\theta_{13}}'$ for ν and $\bar{\nu}$.
- Thus, a combination of ν and $\bar{\nu}$ data is less susceptible to this degeneracy than pure ν data, if the precision on θ_{13} is about 10%.
- We verified this by simulations.

NOνA Experiment

[Ayres et al., NOνA, Tech. Rep. (2007), Fermilab-Design-2007-01]

- 14 kiloton TASD
- 810 km away from Fermilab
- Detector locaton: 0.8° off axis from the NuMI beam
- ν flux peaks sharply at 2 GeV, oscillation maximum energy 1.5 GeV
- Equal ν and $\bar{\nu}$ run of 3 years each
- NuMI beam power 700 kW, corresponding to 6×10^{20} protons on target per year
- We have used retuned signal acceptance and background factor
  [R. Patterson, Talk at *Neutrino 2012*, Kyoto]
  [Sanjib Agarwalla, Suprabh Prakash, Sushant Raut, S. Uma Sankar, arXiv: 1208.3644]

Numerical Simulations

- $\sin^2\theta_{12} = 0.30$, $\Delta_{21} = 7.5 \times 10^{-5}\ eV^2 \longrightarrow$ kept fixed
- $\sin^2 2\theta_{13} = 0.089$, $\sigma(\sin^2 2\theta_{13}) = 10\%$, in preliminary calculations, 5% in later calculations, marginalization done over 2σ range.
- $\Delta m^2_{eff} = \pm 2.4 \times 10^{-3}\ eV^2$, positive (negative) for NH (IH)
- $\Delta m^2_{eff} = \sin^2\theta_{12}\Delta_{31} + \cos^2\theta_{12}\Delta_{32} - \cos\delta_{CP}\sin\theta_{13}\sin 2\theta_{12}\cot\theta_{23}\Delta_{21}$, $\Delta_{31} \simeq \Delta_{32}$ [Nunokawa et al., arXiv: hep-ph/0503283]
- $\sigma(\Delta m^2_{eff}) = 3\%$ [Itow et al., arXiv: hep-ex/0106019], marginalization over $2\ \sigma$ range
- For maximal mixing, $\sin^2\theta_{23} = 0.5$
- For non-maximal mixing, $\sin^2\theta_{23} = 0.41$ for θ_{23} in lower octant and $\sin^2\theta_{23} = 0.59$ for θ_{23} in higher octant
- Marginalization range of $\sin^2\theta_{23}$ is [0.35, 0.65]- $3\ \sigma$ range of global fit
- Marginalization of δ_{CP} is full range- $[-180°, 180°]$

Simulations

Event number simulations and the $\Delta\chi^2$ calculations are done by using GLoBES [Huber et al., arXiv: hep-ph/0407333, Huber et al., arXiv: hep-ph/0701187]

Minimum $\Delta\chi^2$ is calculated by doing a marginalization over the above mentioned parameters.

Effect of Precision of $\sin^2 2\theta_{13}$

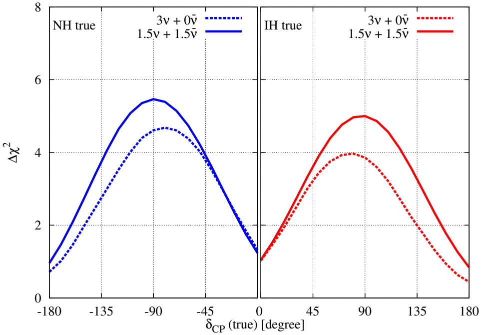

Figure: Hierarchy sensitivity assuming 10% uncertainty in $\sin^2 2\theta_{13}$ and maximal θ_{23}. In the left (right) panel, the true hierarchy is taken to be NH (IH).

If the uncertainty in $\sin^2 2\theta_{13}$ is reduced to 5%, the hierarchy reach for 3ν becomes equal to that of $1.5\nu + 1.5\bar{\nu}$ run. The larger statistics of 3ν data makes this possible.

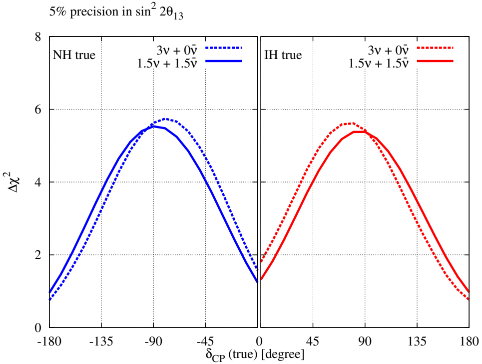

Figure: Hierarchy sensitivity assuming 5% uncertainty in $\sin^2 2\theta_{13}$ and maximal θ_{23}. In the left (right) panel, the true hierarchy is taken to be NH (IH).

Non-maximal θ_{23}

- Recently MINOS experiment measured $\sin^2 2\theta_{23}$ to be non-maximal. [R. Nichol, Talk at *Neutrino 2012* Kyoto, and P. Adamson *et al*, arXiv:1304:6335.]
- We need to worry about an additional degeneracy, ”hierarchy-octant” [Sanjib Agarwalla, Suprabh Prakash, S. Uma Sankar, arXiv: 1301.2574]
- Pure neutrino data is susceptible to this degeneracy whereas combination of ν and $\bar{\nu}$ data is not.

Non-maximal θ_{23}

- Suppose HO is the true octant and NH is the true hierarchy. Then the first term in $P_{\mu e}$ gets a double boost and $P_{\mu e}(\mathrm{NH}) > P_{\mu e}(\mathrm{IH})$ for all parameter values.
- Similarly $P_{\mu e}$ gets a double suppression if LO is the true octant and IH is the true hierarchy.
- For these two octant-hierarchy combinations, pure ν data has a very good hierarchy determination capability.
- But the other two combinations, LO-NH and HO-IH, are nearly degenerate because the boost due to hierarchy is nearly cancelled by the suppression due to octant or *vice-verse*.

Non-maximal θ_{23}

- This degeneracy in $P_{\mu e}$ is resolved by $P_{\bar{\mu}\bar{e}}$.
- For anti-neutrinos, both LO and NH suppress $P_{\bar{\mu}\bar{e}}$ and both HO and IH boost $P_{\bar{\mu}\bar{e}}$.
- NO octant-hierarchy degeneracy in a combination ν and $\bar{\nu}$ data

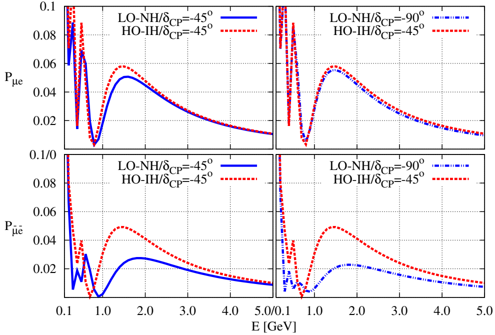

Figure: Illustration of degenerate $P_{\mu e}$ and non-degenerate $P_{\bar{\mu}\bar{e}}$ for the following two cases. Left: (LO-NH, $\delta_{CP} = -45°$) and (HO-IH, $\delta_{CP}{}' = -45°$), Right: (LO-NH, $\delta_{CP} = -90°$) and (HO-IH, $\delta_{CP}{}' = -45°$).

Non-maximal θ_{23}

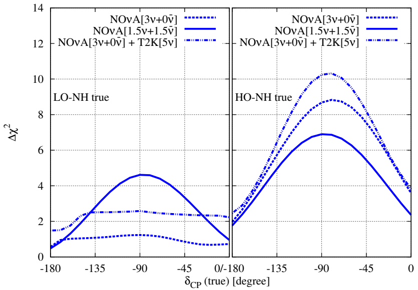

Figure: Hierarchy sensitivity assuming 5% uncertainty in $\sin^2 2\theta_{13}$ for NH and LHP. In the left (right) panel, the true $\sin^2\theta_{23}$ is taken to be 0.41 (0.59).

[Suprabh Prakash, Ushak Rahaman, S. Uma Sankar, arXiv: 1306.4125]

Non-maximal θ_{23}

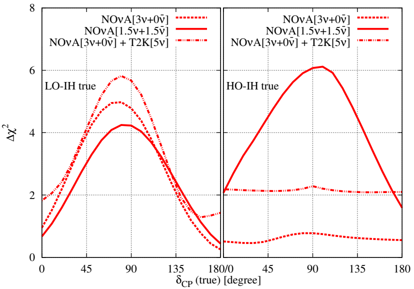

Figure: Hierarchy sensitivity assuming 5% uncertainty in $\sin^2 2\theta_{13}$ for IH and UHP. In the left (right) panel, the true $\sin^2\theta_{23}$ is taken to be 0.41 (0.59).

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Non-maximal θ_{23}

- HO-NH combination has a 2σ hierarchy discrimination for 80% (70%) of the favorable half plane for 3ν ($1.5\nu + 1.5\bar{\nu}$)
- LO-IH combination has a 2σ hierarchy discrimination for 40% (20%) of the favorable half plane for 3ν ($1.5\nu + 1.5\bar{\nu}$)
- For HO-NH and LO-IH$1.5\nu + 1.5\bar{\nu}$ is slightly worse than 3ν.
- For LO-NH and HO-IH, $1.5\nu + 1.5\bar{\nu}$ has a far better sensitivity to hierarchy than 3ν

Conclusion

- $1.5\nu + 1.5\bar{\nu}$ run has a better hierarchy sensitivity than 3ν run, if $\sigma(\sin^2 2\theta_{13}) = 10\%$.
- If $\sigma(\sin^2 2\theta_{13})$ is reduced to 5%, the hierarchy sensitivities of $1.5\nu + 1.5\bar{\nu}$ run and 3ν run are comparable if θ_{23} is maximal.
- For non-maximal θ_{23}, $1.5\nu + 1.5\bar{\nu}$ run good hierarchy sensitivity for all possible hierarchy-octant combinations, where as 3ν has no sensitivity at all for LO-NH and HO-IH
- For these two combinations, addition of T2K data does not help much.
- It is imperative for NOνA to plan on early $\bar{\nu}$ run to get a quick hint of hierarchy for all combinations of octant and hierarchy.


THANK
YOU !